DEVELOPMENT FLIGHT TESTS OF JETSTAR LFC LEADING-EDGE FLIGHT TEST EXPERIMENT

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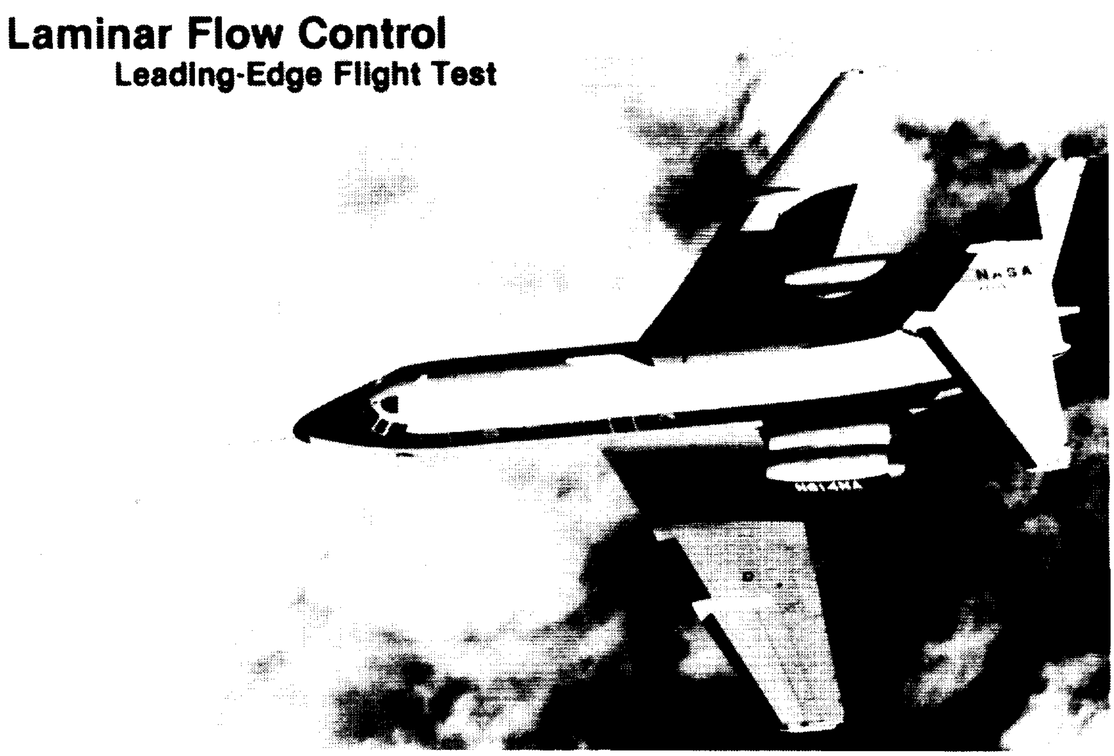
INTRODUCTION

In 1973, fuel economy became more important with the sudden increased cost of fossil fuel due to the Arab oil boycott. This spurred NASA to initiate the ACEE (AirCraft Energy Efficiency) Program (ref. 1) that would seek out technologies that could be applied to aircraft and would save fuel. One technology in aerodynamics that had shown promise (refs. 2 to 9) is laminar flow control where a small portion of the boundary layer near the aircraft skin is removed through slotted or porous skin. It has been estimated that the drag of an aircraft could be reduced 25 to 40 percent (ref. 10) if the wing boundary layer was laminar instead of turbulent. However, laminar flow control had to be shown to be practical. Many of the problems or obstacles to making it practical, such as insect contamination, leading edge attachment line boundary layer, deicing, and suction, involve the wing leading edge. While some of the problems seemed to be solvable (refs. 11 and 12), they had not been incorporated into a single leading- edge design and flight-tested. These problems have been addressed in the JetStar Laminar Flow Control - Leading-Edge Flight Test (LFC-LEFT) Program described in references 10, 13, and 14; the program results are reported here and in references 15 and 16.



OBJECTIVES

The overall objective of these flight tests on the JetStar airplane was to demonstrate the effectiveness and reliability of laminar flow control under representative flight conditions. One specific objective was to obtain laminar flow on the JetStar leading-edge test articles for the design and off-design conditions. The design point for the test articles was M = 0.75 at 38,000 ft and a lift coefficient of 0.3. Off-design points were to be tested from M = 0.7 to 0.8 at altitudes from 32,000 to 40,000 ft, which are representative of the speeds and altitudes that an LFC airplane of the 1990's will be flying. Another specific objective was to obtain operational experience on an LFC leading-edge system in a simulated airline service. This includes operational experience with cleaning requirements, the effect of clogging, possible foreign object damage, erosion, and the effects of ice particle and cloud encounters.

JetStar - Laminar Flow Control

Leading-Edge Flight Test

Overall objective

- **Demonstrate the practicality and reliability of laminar flow control leading-edge systems under representative flight conditions**

Specific requirements

- **Obtain laminar flow on leading-edge test article for design and off-design conditions**
- **Obtain operational experience**
  - Clogging and cleaning requirements
  - Foreign object damage
  - Erosion
  - Ice particle effects

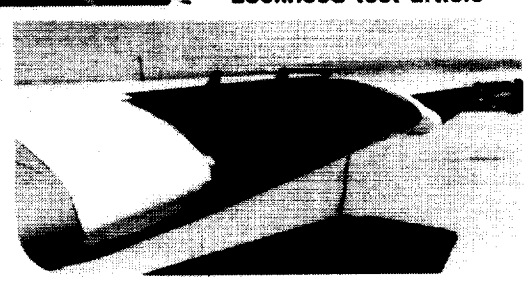
APPROACH

The approach taken to achieve these objectives was to test alternative leading-edge laminar flow control concepts on each wing. Each concept would modify a spanwise section of a JetStar leading edge to include laminar flow control, insect protection, and deicing capability. One leading-edge test article built by the Lockheed Georgia Company uses a slotted skin, while the other test article built by Douglas Aircraft Company uses a porous skin.

At the start of the design of the test articles, NASA and the two contractors agreed that both articles would have the same airfoil shape. The shape agreed upon would have a peak local Mach number of 1.1 for the design test conditions of M = 0.75 at an altitude of 38,000 ft. The leading-edge sweep of the test articles is 30 deg, and each has a span of 61.25 in. Design studies indicated that suction would be needed to have laminar boundary layer flow over the article at design conditions.

- **Modify spanwise section of wing leading edge to include laminar flow control, insect protection, and deicing**
- **Compare alternative concepts**
- **Conduct flight research and airline simulation flights**

Lockheed test article

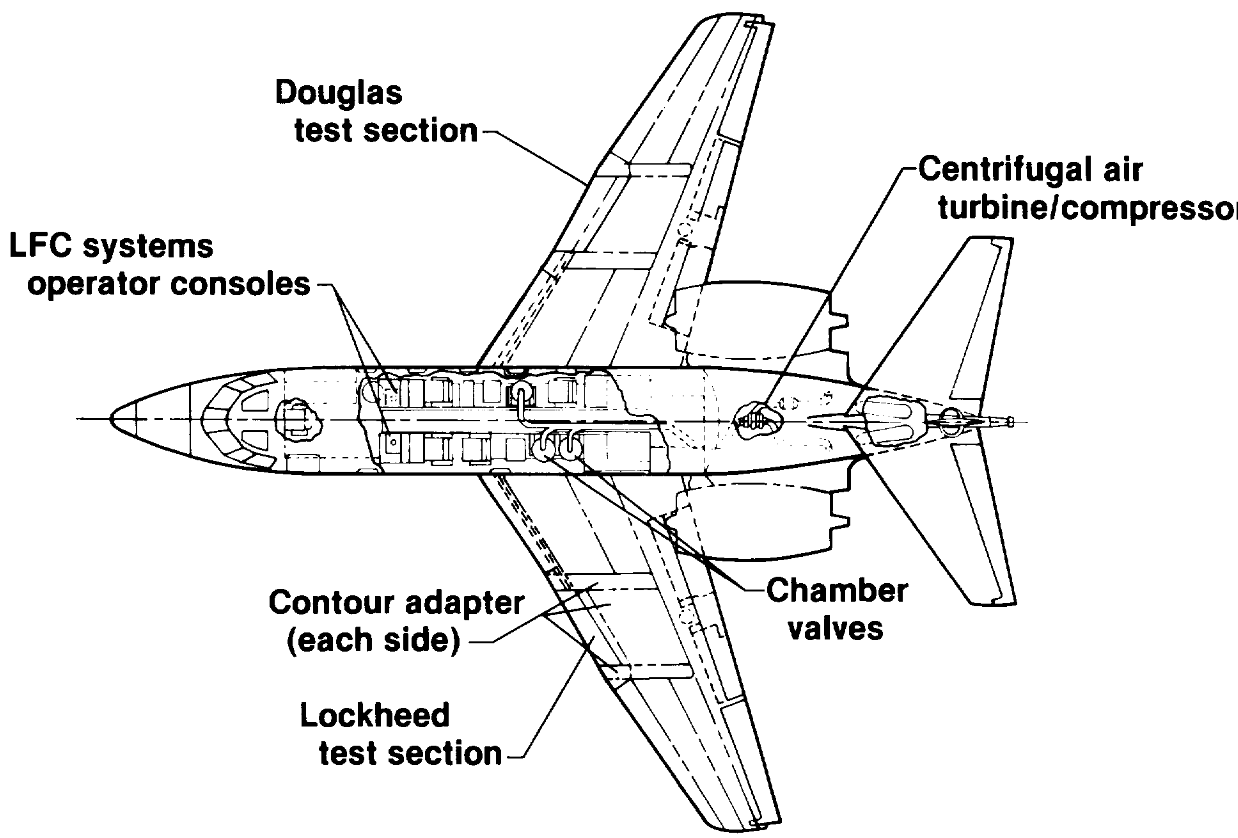


Douglas test article

AIRCRAFT MODIFICATIONS

The JetStar airplane is a business executive jet originally designed to carry 8 to 10 passengers. The aircraft was extensively modified for these flight tests. The auxiliary fuel tanks normally mounted midspan on each wing were removed, and the gap left was filled by leading-edge test articles. Suction tubes from the test articles were routed through the wing leading edges into the cabin of the aircraft to three large plenums or chamber valves. From the chamber valves, the air was then manifolded together and routed aft through the pressure bulkhead to the suction pump. Other major changes to the aircraft included the installation of real-time data and control consoles in the cabin and the cleaning liquid tanks in the aft fuselage.

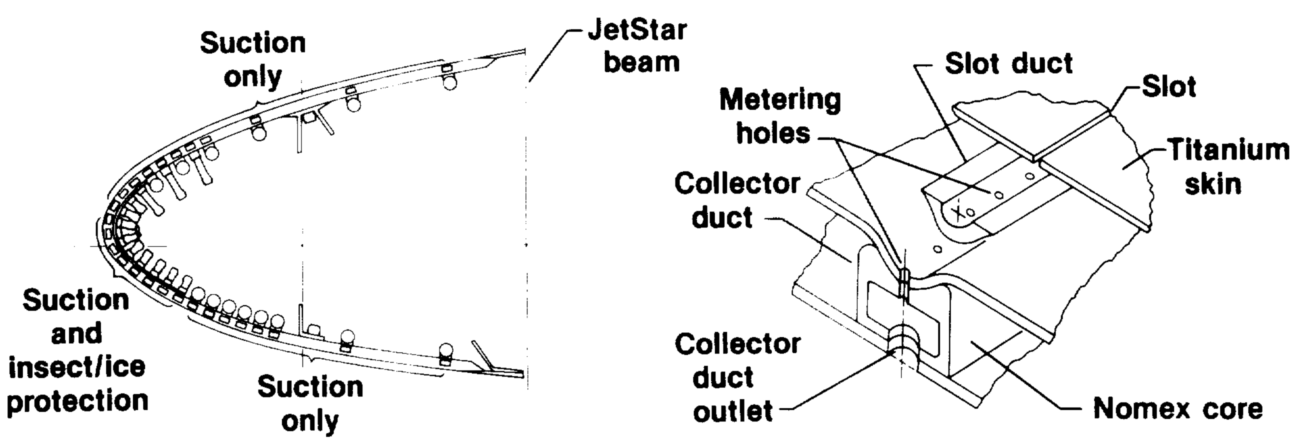
JetStar LEFT Configuration



LOCKHEED-GEORGIA TEST ARTICLE

The test article built by Lockheed Georgia Company is of sandwich construction, comprised of graphite-epoxy face sheets with Nomex (E.I. du Pont de Nemours & Co.) core. The suction surface was formed by cutting twenty-seven 0.004-in spanwise slots on the upper and lower surface. The low-energy surface boundary layer is pulled through these slots into the slot duct. Metering holes were drilled through the slot duct and the outer face sheet in the collector duct. These approximately 0.030-in diameter holes are located on 0.20-in centers. From the collector duct, the air passes through the collector duct outlet holes. These 0.189-in-diameter holes are spaced at approximately 6-in intervals along the surface of the active slot surface. A 60/40 mixture of propylene glycol methyl ether (PGME) and water is expelled through eight of the slots at the leading edge to form a sheet of fluid over the test article for protection from insects and ice.

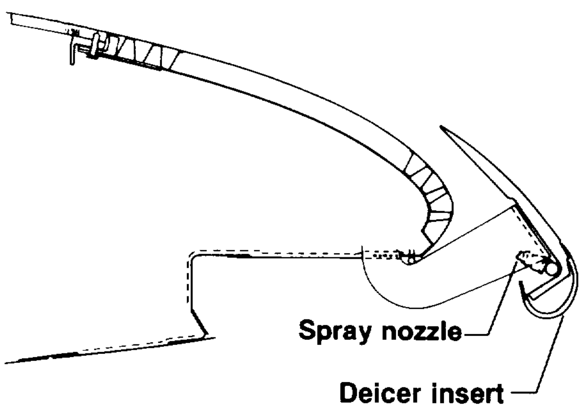
- **Suction on upper and lower surface**
- **Suction through spanwise slots**
- **Liquid expelled through slots for protection from insects and icing**

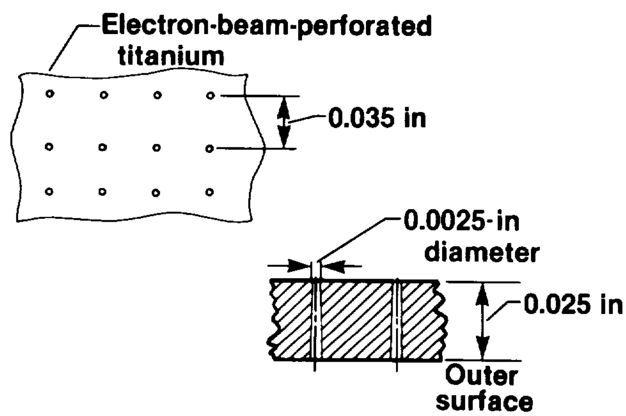


DOUGLAS TEST ARTICLE

Suction was applied only to the upper surface of the Douglas test article. The low-energy boundary layer is drawn through a perforated titanium skin into 15 spanwise flutes. The 0.0025-in holes are drilled with an electron beam and are spaced 0.035-in apart. A leading-edge shield is extended at takeoff and landing for protection from insects. Nozzles behind the shield supplement the shield by spraying PGME on the test article. Protection from ice was provided by extending the shield and secreting a glycol fluid through a porous metal inset at the shield leading edge. The ice protection system can be supplemented by the spray system behind the shield.

- **Suction on upper surface only**
- **Suction through electron-beam-perforated skin**
- **Leading-edge shield extended for insect protection**
- **Deicer insert on shield for ice protection**
- **Supplementary spray nozzles for protection from insects and ice**





LFC SYSTEM OPERATIONS

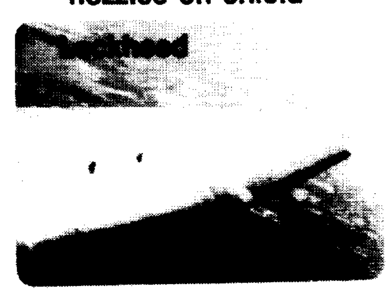
The JetStar airplane had several new systems installed for the LEFT Program similar to those proposed by the contractors for a future Laminar Flow Transport (refs. 17 to 19). The operation of these systems is as follows.

At takeoff, the PGME-water liquid is turned on to protect the Lockheed leading edge from insect contamination. The Douglas test article deploys a leading-edge shield supplemented with PGME-water spray. The secondary purge system, which uses the cabin pressurization system, provides a positive differential pressure in the suction flutes to prevent fluid from entering. At 1000 ft above ground level (AGL), the liquid is turned off and the secondary purge is used to clear the Lockheed suction lines, ducts, and slots. The shield is retracted at 4000 ft AGL. From 12,000 to 23,000 ft, purge air is supplied by the emergency pressurization system. The suction pump, a modified AiResearch turbocompressor originally designed for the air-conditioning system on the Boeing 707 airplane, is started at 20,000 ft. Suction is turned on at the cruise altitude.

LEFT Operations and In-Flight Leading Edge Washing

	Lockheed	Douglas
Takeoff	Liquid on	Shield extended Liquid on Secondary purge on
1,000 ft AGL	Liquid off Secondary purge on	Liquid off Secondary purge on
4,000 ft AGL		Retract shield
12,000 ft	Secondary purge off Primary purge on	Secondary purge off Primary purge on
20,000 ft	Suction pump start	Suction pump start
23,000 ft	Primary purge off	Primary purge off
32,000 ft	Beginning of suction on test article	Beginning of suction on test article

PGME-water liquid sprayed on leading edge through nozzles on shield



PGME-water liquid expelled through leading edge slots

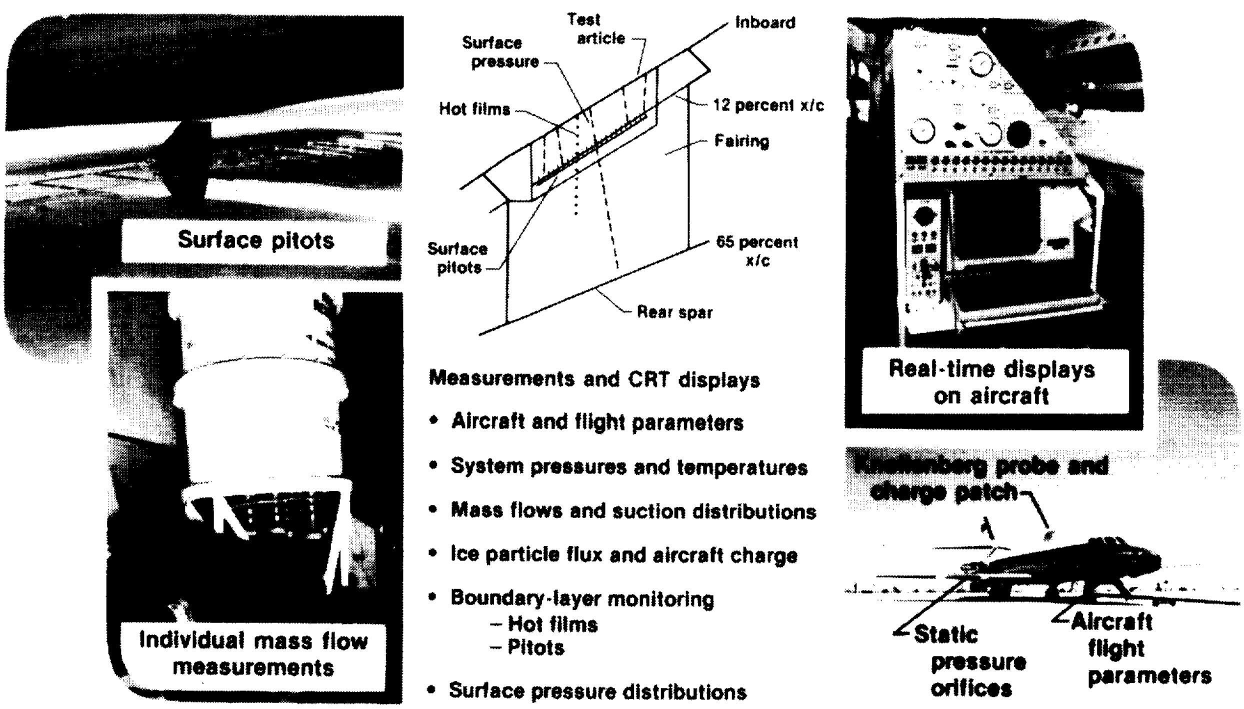
INSTRUMENTATION

Chordwise rows of static pressure orifices were installed on each test article to measure the test article pressure distribution. A chordwise row of hot films was used to detect transition on the Douglas test article. A spanwise row of surface pitots at approximately 13-percent chord was calibrated to determine the extent of laminar flow.

Mass flows and suction distributions for each flute and slot were determined using sonic nozzles located in the chamber valves.

A pylon-mounted Knollenberg probe on the top of the airplane was used to count and size moisture and ice particles during flight. A charge patch on the leading edge of the pylon made a related measurement by detecting the static electric charge built up when flying through the particles. This system is described in further detail in reference 20.

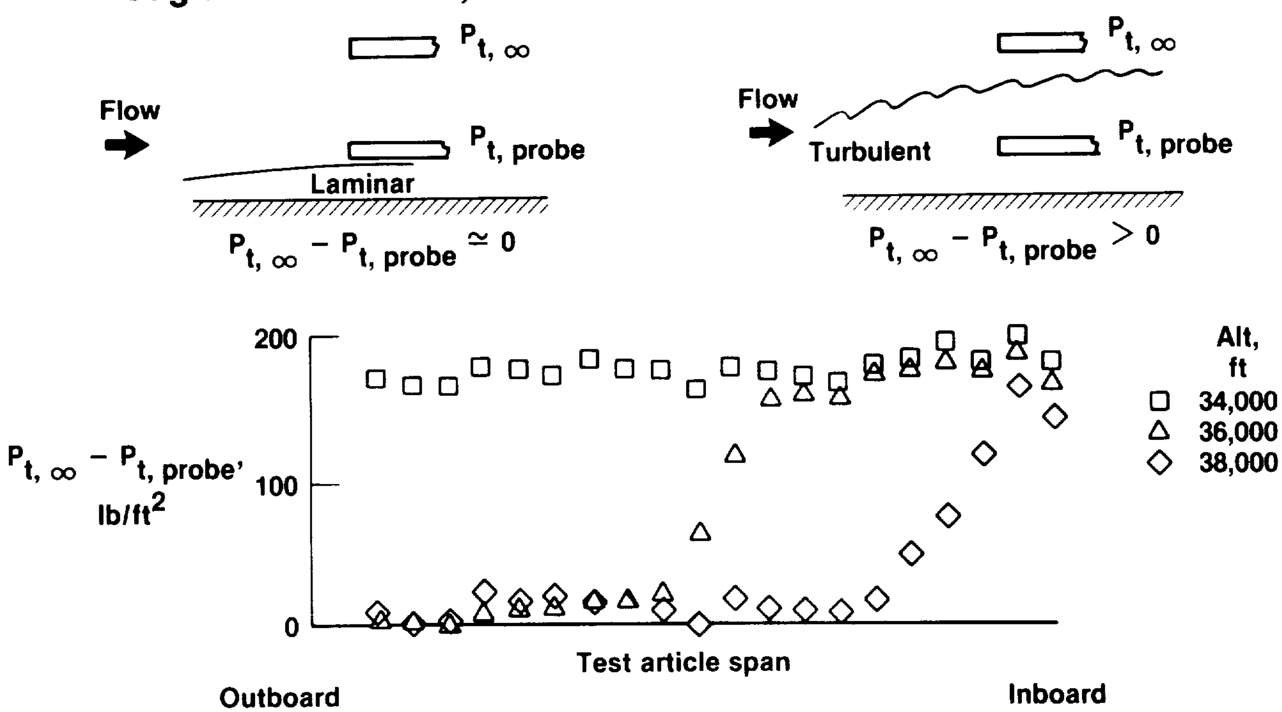
Other miscellaneous pressures and temperatures were measured to monitor the operation and health of the suction pump and other leading-edge systems as well as basic aircraft parameters. These measurements were displayed in real time on the operator control consoles in the airplane cabin.



Transition was detected using a spanwise array of pitots located near the surface of the test article skin at x/c ~ 0.13. The probe height was positioned to be just outside the thin boundary layer when the boundary layer was laminar; for the thicker turbulent boundary layer, the probe would therefore be immersed in this boundary layer. A reference probe measuring the free-stream pressure was located nearby. Transition was determined by comparing the pressure from the spanwise pitots with the free-stream pressure. For laminar flow, differential pressure is nearly zero. For a turbulent boundary layer, the free-stream pressure is higher. These spanwise probes were calibrated for transition location by placing spanwise transition strips at known x/c locations on the test article.

Determination of Extent of Spanwise Laminar Flow From Pitot Data

Douglas Test Article; M = 0.75

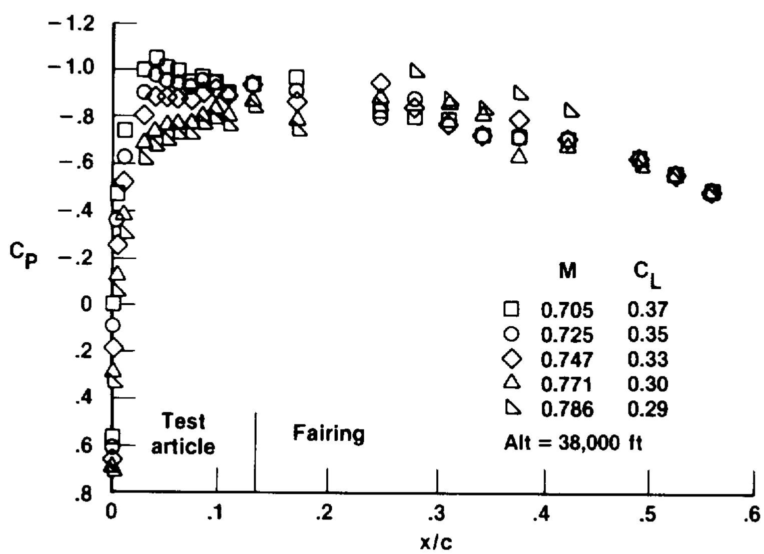


PRESSURE DISTRIBUTIONS

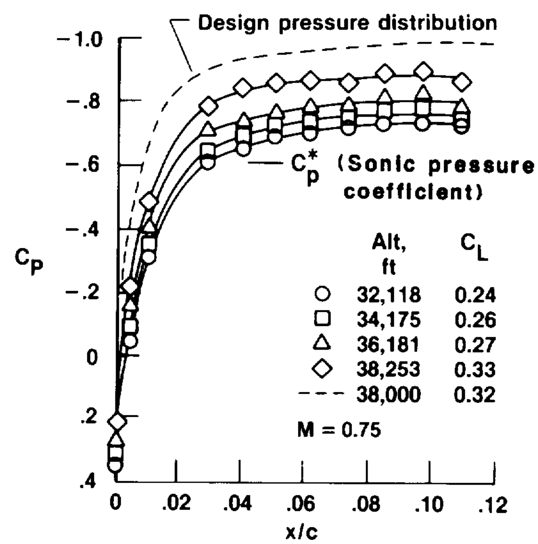
The pressure distributions measured in flight show the effects of varying Mach number between 0.705 and 0.786 at an altitude of 38,000 ft. The pressure distribution for the lowest Mach numbers had a steep suction peak with an adverse pressure gradient beginning at x/c = 0.04. The pressure distributions at the higher Mach numbers had a less steep suction peak with the adverse gradient delayed.

The variation of pressure distributions on the test articles as a function of altitude and lift coefficient C_L is shown. As the altitude and C_L increase, the pressure coefficients become more negative as expected. For comparison, the design pressure distribution is shown. While the local Mach number for the design case is slightly higher, M = 1.16 as compared to M = 1.12 for flight, the pressure gradients are similar.

Douglas Test Article; Midspan



Variation with Mach number

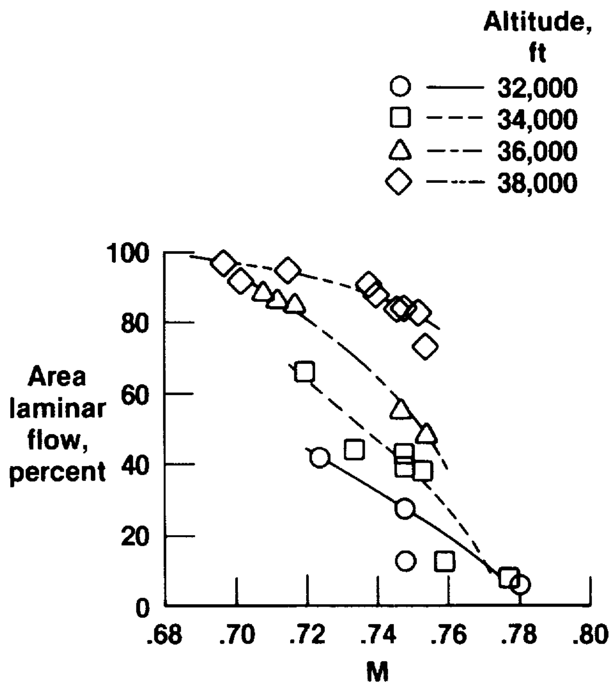


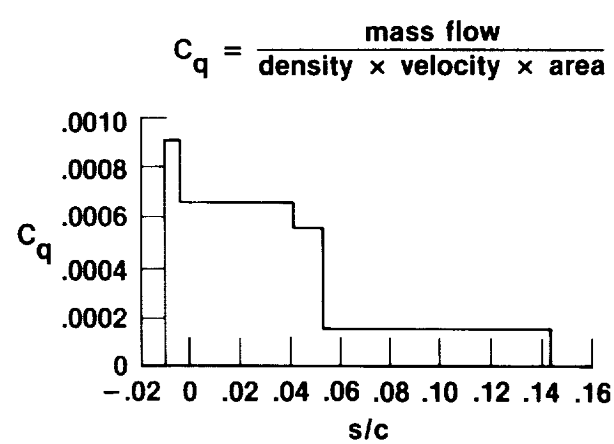
Variation with altitude

INITIAL FINDINGS - DOUGLAS TEST ARTICLE

For the nominal suction distribution used initially for the Douglas test article, a high degree of suction (suction coefficient C_q = 0.0009) was applied at the leading edge. After the first flute, the suction was reduced to C_q = 0.00065 to approximately s/c = 0.05 (ratio of surface length to chord length). From s/c = 0.05 to the test article trailing edge, a threshold level of C_q = 0.00016 was maintained.

The initial findings for the Douglas test article show the area of laminar flow on the test article as a function of Mach number. These data are derived from the 20 surface pitot probes at the test article trailing edge. Approximate transition locations were determined and laminar areas derived. This figure shows that the test points at the lowest speeds and highest altitudes (that is, the lowest Reynolds number) resulted in the most laminar flow. Conversely, the data at the lowest altitudes and highest speeds (that is, the highest Reynolds numbers) resulted in the least laminar flow. At the design point, approximately 83 percent of the test article was laminarized. At the off-design point of M = 0.705 and 38,000 ft, 97 percent of the test article had laminar flow, whereas at M = 0.78 and 32,000 ft, this value was only 7 or 8 percent.

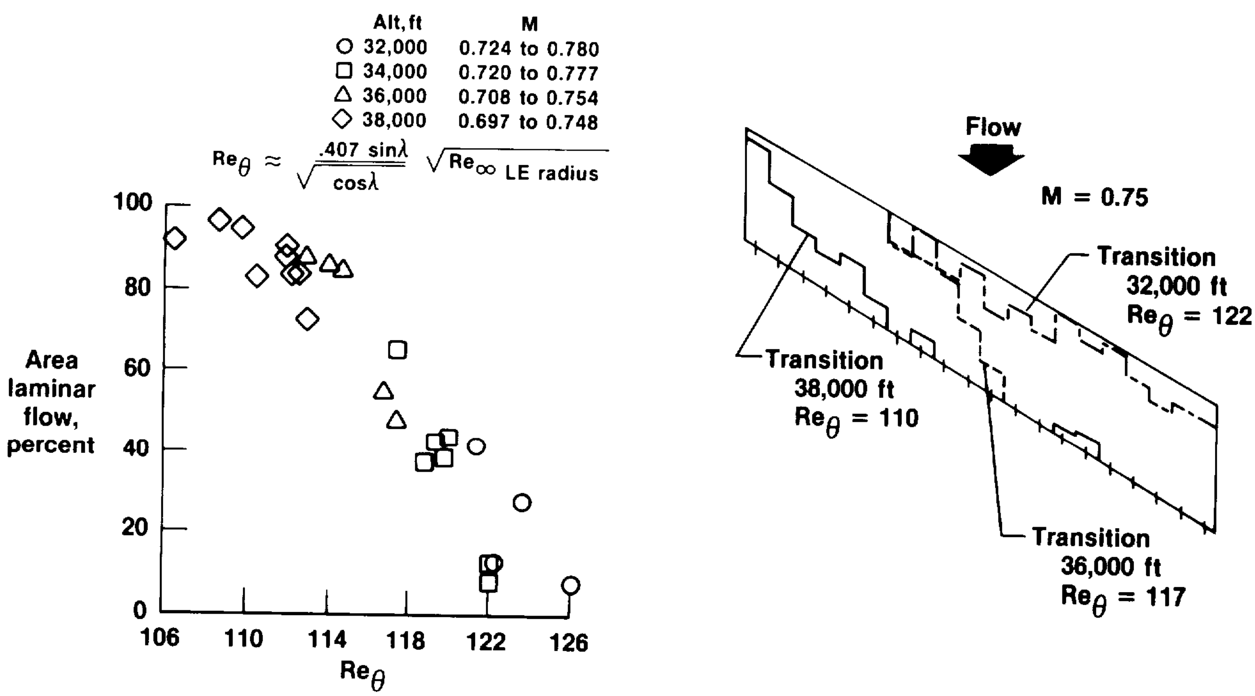




The spanwise transition location on the Douglas test article moved from inboard to farther outboard as the altitude was reduced and the Reynolds number was increased. The initial findings from the Douglas test article have been replotted as a function of momentum thickness Reynolds number, Re_θ. As Re_θ was reduced to values to near the X-21 criteria of 100, the extent of laminar flow approached 100 percent. This suggests that the attachment line boundary layer was traveling outboard along the wing leading edge and caused the flow on the test article to transition from laminar to turbulent flow. The X-21 criteria indicate that if $Re_\theta < 100$, the turbulent boundary layer from the fuselage and inner wing will not travel along the leading edge but will be swept back over or under the wing.

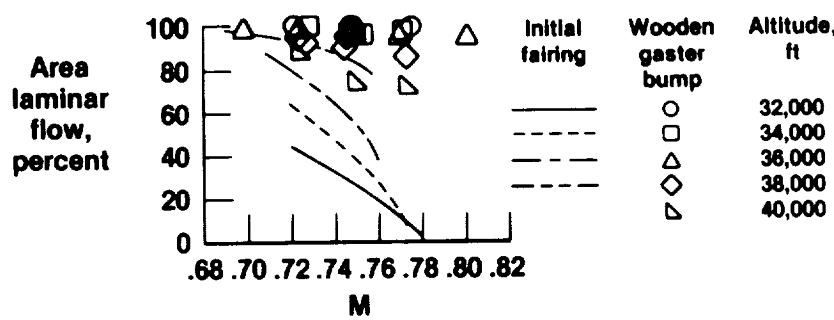
Evidence of Spanwise Contamination

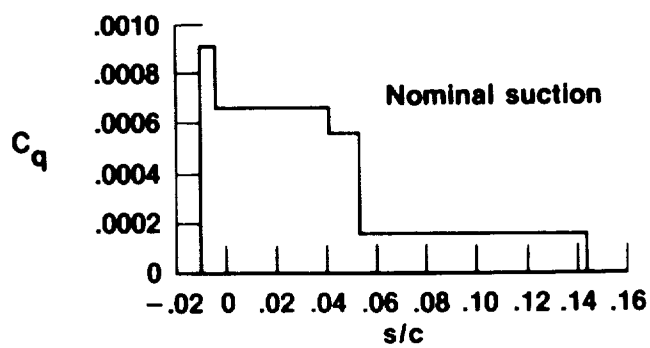
Douglas Test Article; Initial Fairing



WOOD GASTER BUMP - DOUGLAS TEST ARTICLE

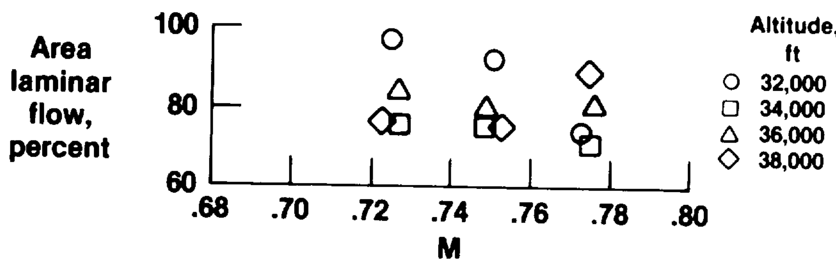
During tests with a half-span swept laminar flow control wing in the wind tunnel and in flight on a Lancaster bomber, Gaster (ref. 21) developed a small protrusion or leading-edge bump to alleviate this turbulent attachment line boundary-layer problem. A similar bump made of wood was attached and faired in at the approximate attachment line of the Douglas test articles as shown. The results of this modification using the same suction distribution as previously are also shown. At an altitude of 32,000 ft and M = 0.72 to 0.75, the test article was completely laminar across the span. The data from 34,000 and 36,000 ft show the test article to be at least 95-percent laminar. A slight degradation was noted as the Mach number was increased. The data from these altitudes show a marked improvement compared to the initial findings. The data at 38,000 ft with the wood Gaster bump show some improvement compared to the initial fairing. At the design point, M = 0.75 at a 38,000-ft altitude, about 90 percent of the surface was laminar as compared with 83 percent with the original fairing. However, at 40,000 ft, the data with the wood Gaster bump had less laminar flow than the initial findings at 38,000 ft.

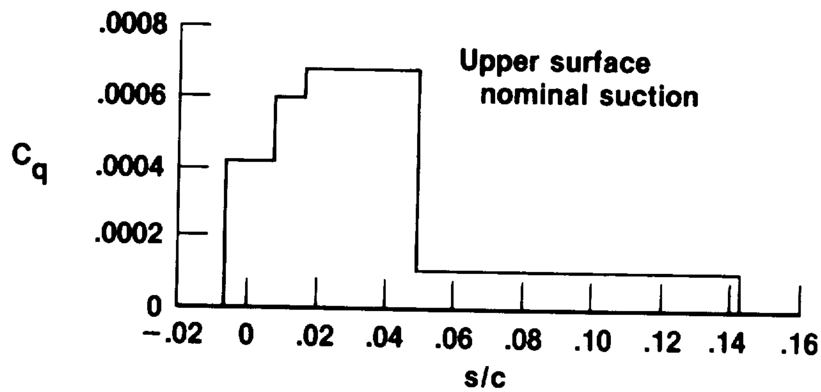




WOOD GASTER BUMP - LOCKHEED TEST ARTICLE

A similar wood leading-edge bump was installed on the Lockheed test article. The suction distribution on the Lockheed test article differs from the Douglas suction distribution in that the Lockheed test article used less suction at the leading edge. With the wood leading-edge bump, approximately 97 percent of the surface was laminarized at M = 0.725 and an altitude of 32,000 ft. However, at M = 0.775, the area of laminar flow was reduced to 74 percent. At the higher altitudes, the area of laminar flow ranged from 70 to 90 percent, with most of the data below 80 percent. At the design point, M = 0.75 at a 38,000-ft altitude, approximately 75 percent of the test article was laminarized.

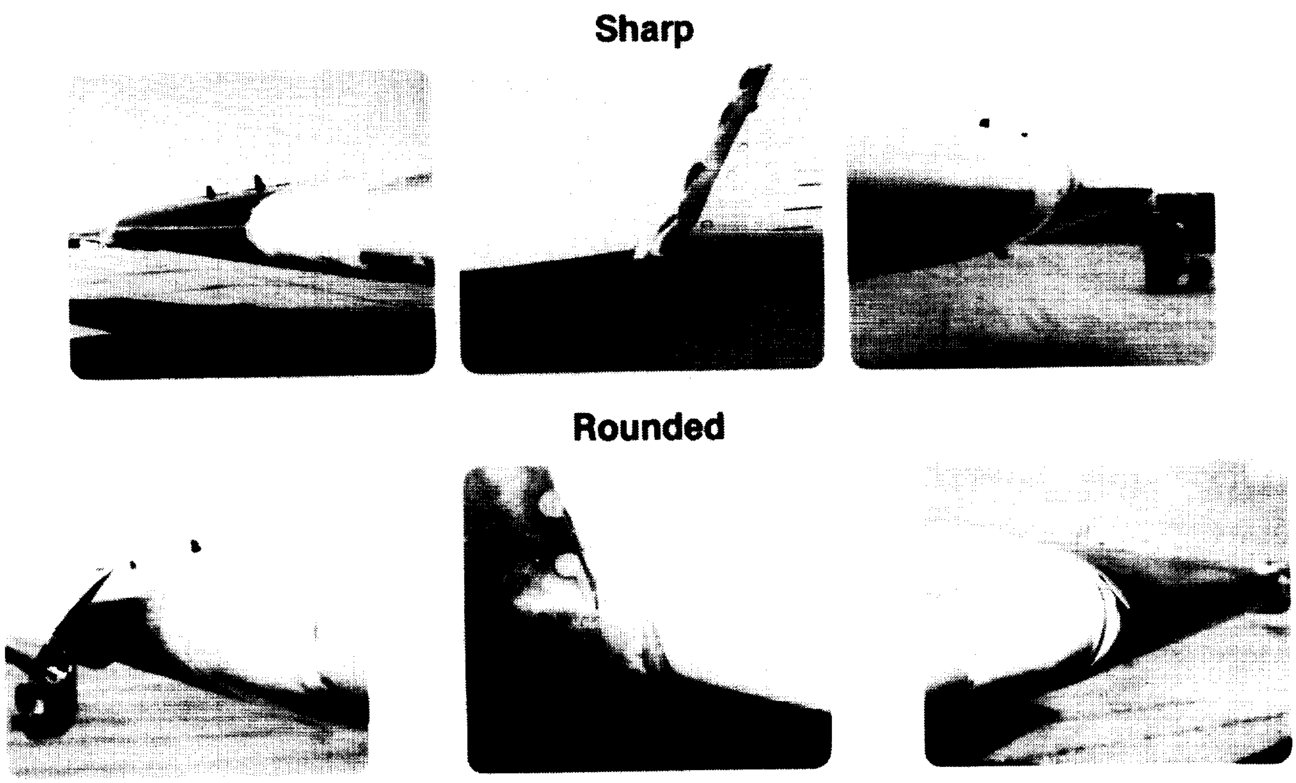




SHARP AND ROUNDED LEADING-EDGE NOTCHES

In preparation for the simulated airline service flights, it was believed that more permanent integral leading-edge bumps were needed, and also that their performance of achieving laminar flow on the test articles could be improved.

The first approach tried was to modify the inboard fairings with a notched leading edge that would divert the turbulent attachment line boundary layer at the leading edge over or under the wing. Both a sharp notch and a rounded notch were tested. The test results of both notches showed little or no improvement over the initial fairings; the notches were much worse than the wood Gaster bumps.

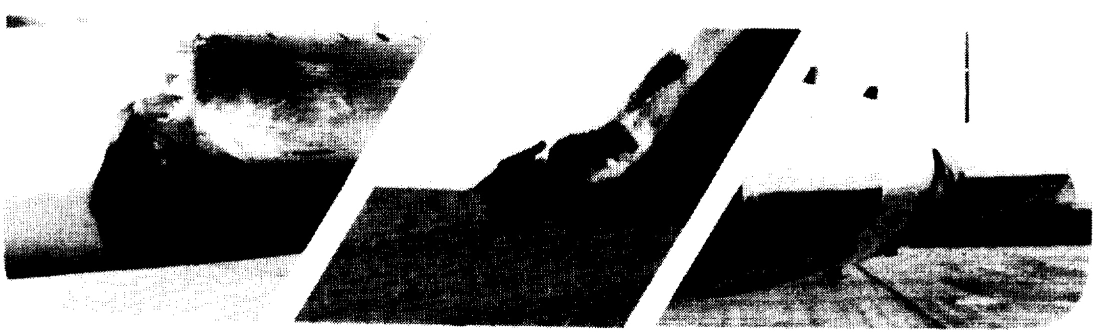


LEADING-EDGE NOTCH-BUMPS

Although the depth of the notch was approximately the height of the wood Gaster bumps, the notches did not achieve the same favorable effect. One difference between the Gaster bumps and the notches was the local leading-edge radius. The notches had the same leading-edge radius as the initial fairing (about 2.0 in), whereas the Gaster bumps had a much smaller radius, about 1.0 in. The smaller leading-edge radius reduced the momentum thickness Reynolds number Re_θ from about 128 for M = 0.78 at an altitude of 32,000 ft to about 90, which is well below the X-21 criteria of 100 and corresponds to Gaster's own criteria of 90. The notches inboard on the Douglas and Lockheed test articles were then modified into an integral notch-bump to reduce the leading-edge radius to ~ 1.0 in.

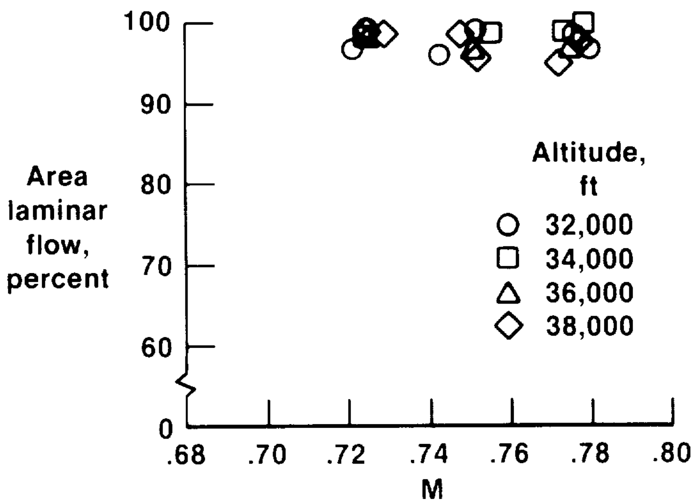
Douglas Test Article

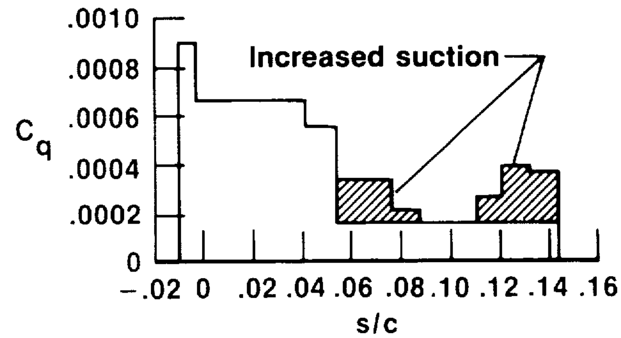
Lockheed Test Article



DOUGLAS TEST ARTICLE RESULTS WITH LEADING-EDGE NOTCH-BUMP

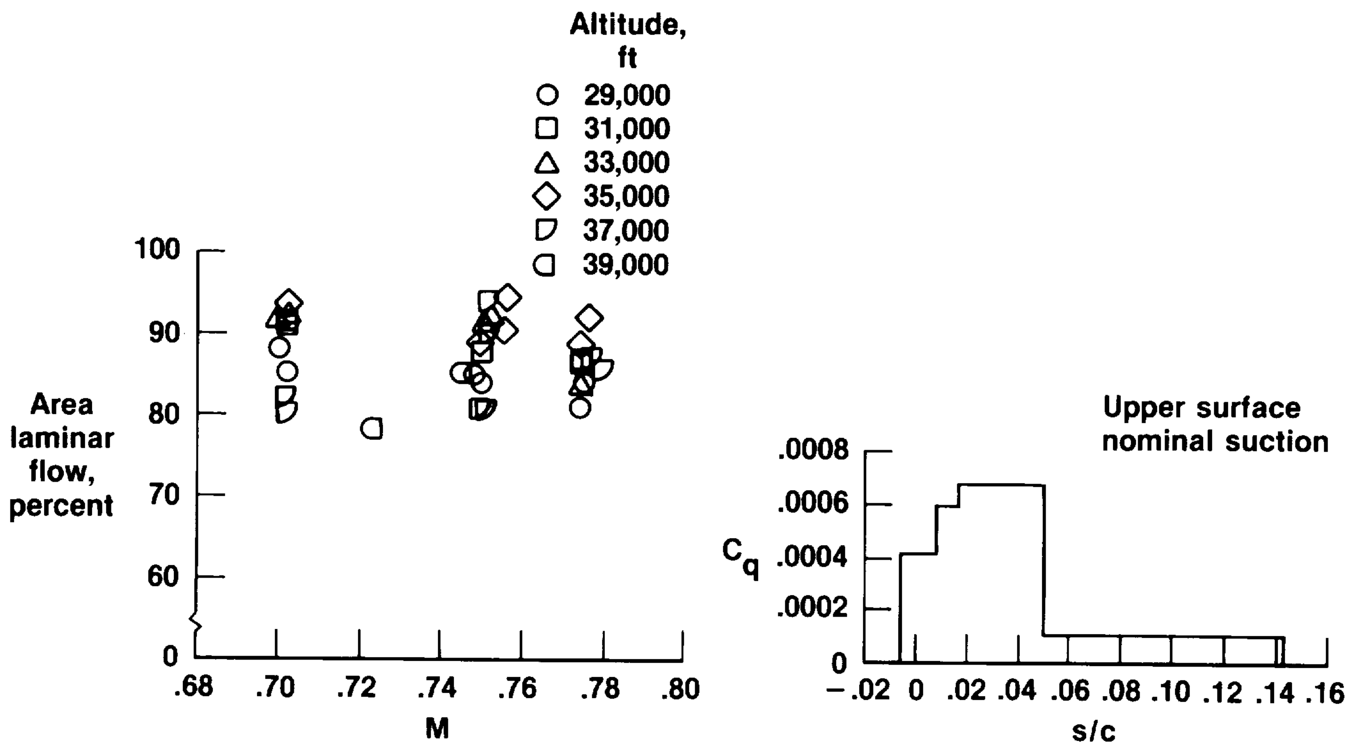
The results of the data for the notch-bump are compared with those for the wood Gaster bump. At all altitudes, the Douglas test article with the notch-bump modification showed as much or more laminar flow as with the wood Gaster bump. The suction distribution had been modified at this time, as shown, to provide increased suction in the aft flutes. This allowed the test article to achieve nearly fully laminar flow over the entire test article at the conditions tested. At the design test condition, M = 0.75 and an altitude of 38,000 ft, the test article was 96-percent laminar.





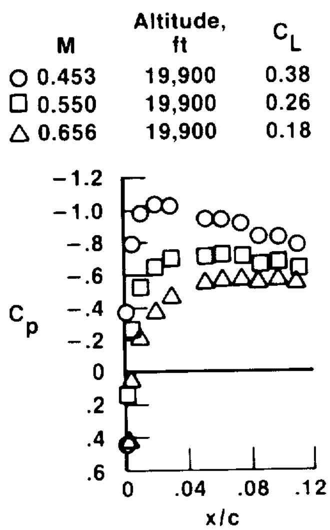
LOCKHEED TEST ARTICLE RESULTS WITH LEADING-EDGE NOTCH-BUMP

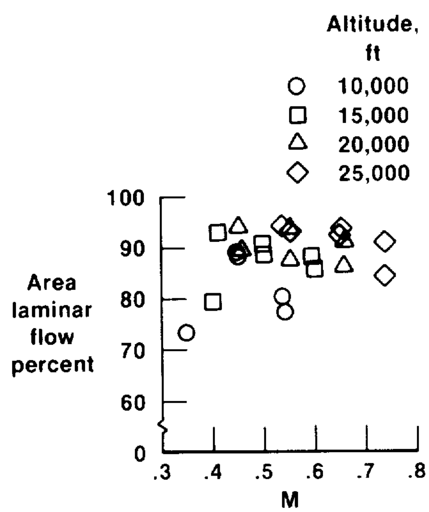
The Lockheed test article with the leading-edge notch-bumps did not maintain laminar flow as consistently as the Douglas test article. Near the design conditions, the test article surface varied between 80- and 94-percent laminar. At other Mach numbers and altitudes, the data were also scattered. These results are probably the effect of the manufacturing problems encountered in making the slotted test article, which caused uneven suction, surface waviness, and blocked slots.

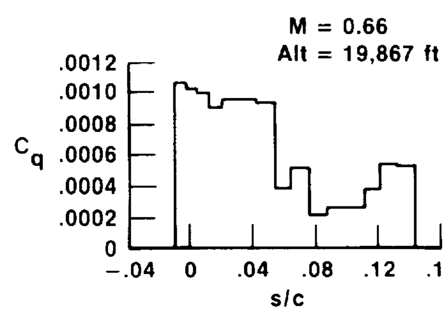


LOW-ALTITUDE RESULTS OF DOUGLAS TEST ARTICLE WITH NOTCH-BUMP

Additional testing of the Douglas test article at low altitude was conducted to determine if the test articles could be laminarized during the climb or descent portion of the flight. Tests were conducted at altitudes of 10,000, 15,000, 20,000, and 25,000 ft at three Mach numbers. Sample pressure distributions are shown. At the lowest Mach number and the highest angle of attack, a suction peak occurs in the pressure around 2 percent chord, followed by an adverse pressure gradient. At the highest Mach numbers and lowest angle of attack, a favorable gradient was present to approximately 7.5 percent chord. For these tests, because an LFC transport would probably use fixed valve settings, the same needle valve positions as for the design point were used. Even with this nonideal suction, the test article was approximately 90-percent laminar.



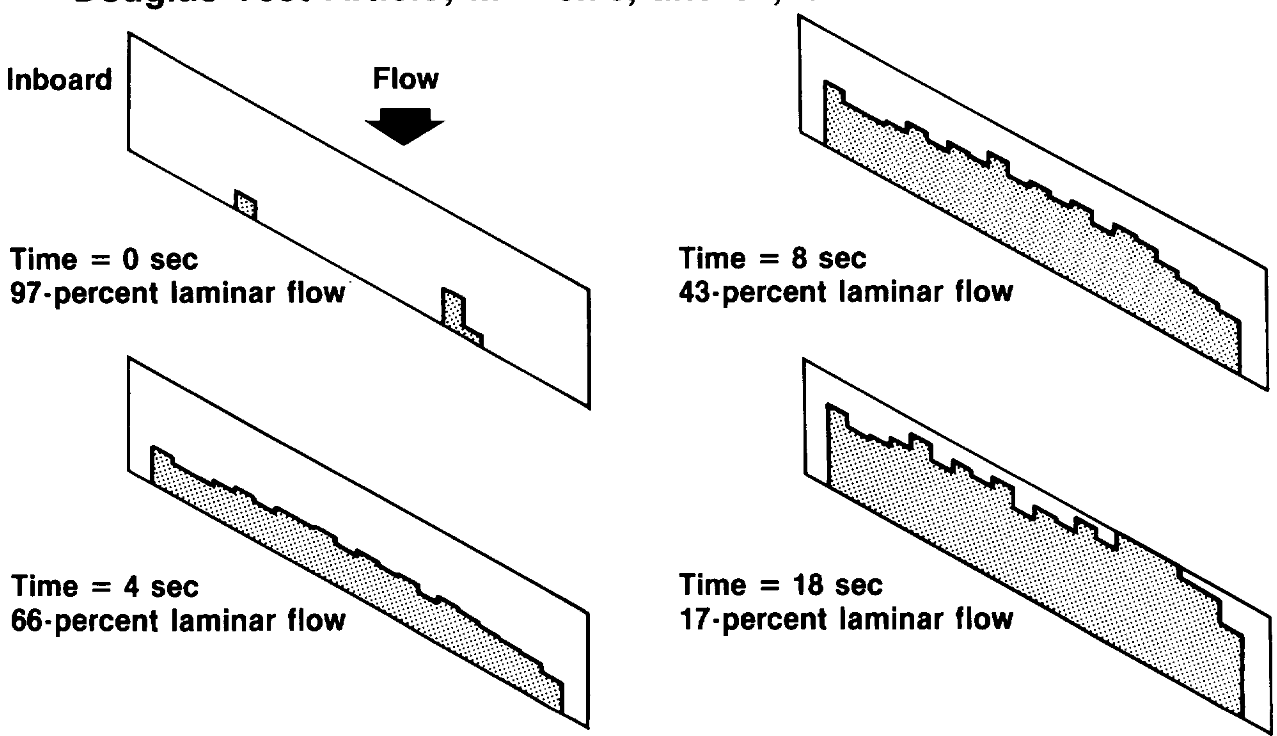




EFFECT OF CLOUDS AND ICE PARTICLES ON LAMINAR FLOW

During the flight tests of the leading-edge test articles, flight through clouds and ice particles at high altitude occurred. The results of these encounters are shown. Laminar flow on the test article was lost while encountering the clouds and ice particles but was restored immediately upon leaving the clouds and ice particles. This agrees with ice particle data obtained on the X-21A aircraft (ref. 8).

Douglas Test Article; M = 0.76, and 34,200 ft. Altitude



CONCLUDING REMARKS

The JetStar LFC Leading-Edge Flight Test Program development flights gave the following results:

1. The Douglas and Lockheed leading-edge test articles have been successfully installed and systems operated.

2. Attachment line contamination was present with the initial inboard fairings. Gaster bumps or leading-edge notch-bumps were effective in solving this problem by reducing the leading-edge momentum thickness Reynolds number to 90 or less.

3. The Douglas test article with the leading edge notch-bump configuration was 96-percent laminarized at the design point. In addition, the article was at least 95-percent laminarized for M = 0.72 to 0.78 and altitudes of 32,000 to 38,000 ft. Laminar flow on the Lockheed test article with the leading-edge notch-bump was inconsistent. Near the design point, the test article was laminarized from 80 to 94 percent.

4. Laminar flow was lost while encountering clouds or ice particles but was regained to previous levels after leaving the clouds or ice particles.

- **Two LFC leading-edge test articles have been successfully installed and operated**

- **Attachment line contamination problem was solved using Gaster bumps and notch-bumps**

- **Douglas test article was nearly fully laminarized at the test conditions. Lockheed test article was laminarized from 80 to 94 percent at the design conditions**

- **Laminar flow was lost on test articles during encounters with clouds and ice particles. Laminar flow was immediately regained after exiting the cloud or particles**

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